# A SYSTEMATIC APPROACH TO CASE RECERTIFICATION

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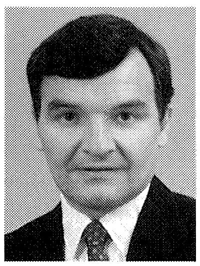

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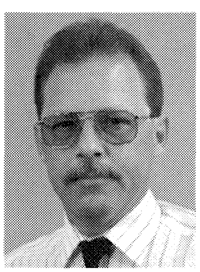

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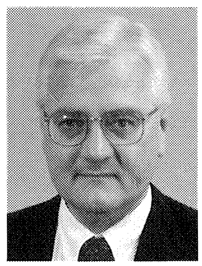

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## ABSTRACT

Turbomachinery life expectancy, economic conditions, and plant capacity enhancements have created a need for vintage compressors to be reevaluated and re-engineered for operational parameters that may not have been incorporated in the original design. Aerodynamic revamps have been standard practice for optimizing flow conditions to today's processes. These changeouts have traditionally been limited to manipulation within designed pressure ratings.

Recently, in addition to the aerodynamic enhancements, processes are requiring increased pressure levels. These new requirements and requests have posed questions and concerns which have not been of predominant importance previously. Integrity of the containment vessel, leakage of process gases, condition, and life expectancy at above design conditions must be addressed to make an informed comparison between a rerate and purchase of replacement equipment.

The hazards and possible expenses of operating turbomachinery above rated pressures without a systematic and consistent verification process should be avoided. Hence, a new field has been undertaken by OEMs driven by equipment user request, to certify existing casings at increased levels in the safest and most reliable manner. The following guidelines have been produced to conduct

such rerates with minimal risk to the compressor case and thus, the processes in which these machines play an intricate part:

- Specific case testing history
  - Examine records and designs to determine if the casing has been hydrotested previously, or has been hydrotested to appropriate new condition levels.
- Review of similar vintage machinery
  - Review designs of similar machines built in the same era to determine if ratings have ever been within appropriate levels.
- Analyze the specific case design
  - Analyze the case with the use of modern and proven finite element methods to verify the integrity of the case design at elevated pressures based on blueprint dimensions. Review data with the user, discussing concerns of both parties and come to a consensus whether a hydrotest is feasible.
- Inspect and review
  - Inspect the case per manufacturing blueprints to verify thickness and overall condition of the case and continuity of FEA model. With the use of magnetic particles, inspect the casing for indications and discontinuities which could endanger the casing during the hydrotest. Review the data and determine if continuation of testing is feasible.
- Strain gauge casing
  - Place strain gauge equipment at key high stress locations based on FEA model to protest casing during hydrotesting.
- Hydrotest case
  - With online strain readings, hydrotest casing to the appropriate levels. Carefully monitor the strain data to protect the casing from going beyond prescribed stress levels at the desired pressure levels. If stress levels appear to be approaching recommended limits, consensus should be made on whether to continue.
- Recertification
  - After a successful hydrotest, rerate the compressor name plate and records for the new pressure level.

The following paper will use a case history as a step by step example to show how case recertification has been accomplished in the safest possible manner with minimal risk to equipment.

## INTRODUCTION

Turbomachinery life expectancy, economic conditions, and plant capacity enhancements have created a need for vintage compressors to be reevaluated and re-engineered for operational parameters that may not have been incorporated in the original design. Aerodynamic revamps have been standard practice for optimizing flow conditions to today's processes. However, these changeouts have traditionally been limited to manipulation within designed pressure ratings.

Recently, in addition to the aerodynamic enhancements, certain processes are requiring increased pressure levels. These new requests and requirements have posed questions and concerns that have not been of predominant importance in the past. Integrity of the containment vessel, leakage of process gases, and condition of the casing at higher than original design conditions must be addressed to make an informed comparison between a rerate and purchase of replacement equipment.

Potential hazards and possible expenses of operating turbomachinery above rated pressures without a systematic and consistent verification process must be avoided. Hence, a new field has been undertaken by original equipment manufacturers (OEMs), driven by equipment user request, to certify existing casings for operation at increased pressures in the safest and most reliable manner. Guidelines have been established to conduct such rerates with minimal risk to the compressor case and thus, the processes in which these machines play an intricate part.

### *Case History*

The following example reflects the activities associated with one such casing rerate.

In 1993, one customer (a domestic steel mill) advised that operation of an existing 124 in centrifugal compressor at increased discharge pressure would be desirable. The required new discharge pressure would be 48 psig.

The compressor in question was supplied originally in 1951 and is currently used for blast furnace air. The compressor originally was sold with a discharge pressure rating of 35 psig, and was rerated in 1969 to provide increased flow and 40 psig discharge pressure. The casing is of the horizontally (axially) split type and has a nominal inside diameter of 121 in. In addition to the horizontal split, there is a vertical (radial) split at the first impeller stage position, separating the inlet (low pressure) casing from the discharge (high pressure) casing. The main inlet flange is circular with a 66 in diameter, while the discharge flange is rectangular with dimensions of 40.0 in × 29.5 in. Both the inlet and discharge flanges are located in the bottom of the case. Records indicated that this particular casing had never been hydrotested.

### *Review of Similar Vintage Machinery*

Further search of the records indicated that there had been at least 111 of the 124 in casings manufactured. There had also been at least five 140 in casings manufactured, which utilize a similar discharge end casing to that used for the 124 in. The majority of these units were built prior to the late 1950s.

This was before API 617 was adopted as the industry standard for centrifugal compressors, which requires that compressor casings be hydrostatically tested at 150 percent of their rated pressure. Furthermore, in the same time period that hydrotest requirements were established, the 124 in casing material was changed from 30 ksi ultimate tensile strength (UTS) cast iron to 40 ksi UTS cast iron.

It was concluded that none of the 30 ksi casings had ever been hydrotested. Stress-strain curves for cast iron show no distinct yield point. The stress-strain curves for 30 ksi and 40 ksi materials are sufficiently different to preclude the application of results of hydrotest of one to the other.

Since none of the 30 ksi material cases had ever been hydrotested, further review of the records was undertaken to determine whether any of those units had ever been sold for and/or operated at pressures approaching the required 48 psig. This review revealed that prior to 1965, none of these units had ever been sold for operation above 35 psig. A unit was sold in 1965 for operation at 40 psig discharge pressure. However, that 40 psig was the maximum rating for which any 124 in casing had ever been sold, and that casing was constructed of 40 ksi UTS material. The first similar unit applicated above the desired 48 psig was a 140 in unit sold in 1970. This unit was rated for 50 psig. Records indicated that the discharge casing for this 140 in unit had been hydrotested.

### *Analyze the Specific Case Design*

In order to determine whether results of the 140 in discharge casing hydrotest could be extrapolated to apply to the subject casing, a comparison of the designs of the two discharge end casings was undertaken.

Inlet end casings were not considered since on air compressors of this type, the inlet end is never subjected to pressures above the existing 40 psig rating. The following tabulation reflects a comparison of the hydrotested unit (serial number (s/n) B-2966) with the unit in question (s/n B-1411):

| | | |
|---|---|---|
| s/n | 1411 | 2966 |
| Year Built | 1951 | 1970 |
| Rating (psig) | 40 | 50 |
| Hydrotest Press (psig) | n/a | 75 |
| Disch. Case Matl. | Cl 30 Gray Cast Iron | Cl 40 Gray Cast Iron |
| Tensile Strength (psi) | 30,000 | 40,000 |
| Horiz. Flg. Thickness (in) | 3.5 | 4.625 |
| Rib Height (in) | 3.0 | 5.5 |
| Number of Ribs | 7 + 7 | 7 + 7 |
| Minimum Thickness | 1.5 | 1.5 |

As evidenced by the tabulation, casing design (material, flange thickness, and strengthening rib height) of the hydrotested unit, s/n B-2966, was significantly different from that of s/n B-1411.

Based on the above study, there was no evidence to indicate that the casing in question, s/n B-1411, was capable of the desired 48 psig discharge pressure. The customer was therefore advised that operation at 48 psig could not be recommended without:

- Finite element analysis (FEA) to determine theoretically the case pressure capability, and to determine hydrotest feasibility.
- Inspection to assure that the case met print requirements and had not experienced any excessive wear or rework. If feasibility is indicated,
- Hydrotest of the casing to the required 72 psig (150 percent of operating pressure). The casing would be strain gauged to enable monitoring of key stress areas during the hydrotest.

*Finite Element Analysis of Specific Case*

A FEA of the MTA 5124 casing was performed with the understanding that final acceptance of the uprated pressure had to be based on the actual hydrotest results.

Only the discharge end was modelled. This model, illustrated in Figure 1, contains over 26,000 nodes and over 18,000 brick type (eight noded) elements. Beam elements, each with a 60,000 psi simulated preload, were used to represent the bolts connecting the upper and lower halves at the horizontal flanges.

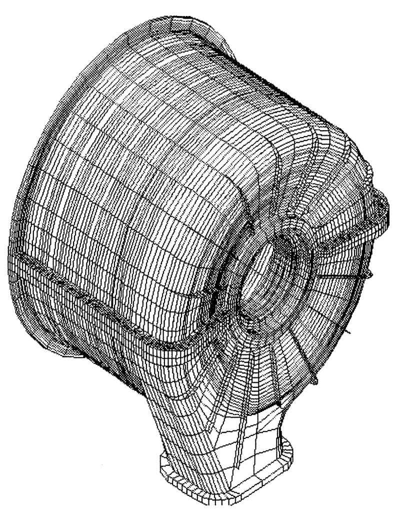

*Figure 1. FEA Model of Discharge End of MTA 5124 Casing.*

In an effort to reduce analysis time and computer run time, the intake end of the casing was not modelled. The intake end does effect the response of the discharge end, since they are connected at the vertical flange.

In order to ensure that conservative results for the discharge end were obtained, several sets of boundary conditions at the vertical flange were used in the analysis runs. In one run the flange was constrained axially but was completely free to grow radially. This represents a situation where the internal pressures and case geometries result in the discharge casing flange and intake casing flange deforming radially by the same amount. In another run, the vertical flange was restrained axially and radially. This represents a situation where the intake casing flange does not deform radially at all, and completely prevents the discharge casing flange from growing. The true behavior of the vertical flange lies somewhere between these two extremes. An iterative scheme was used to determine areas of contact and separation at the horizontal flange, allowing the determination of leakage.

Stresses at the hydrotest condition were calculated using the FEA model. The highest stresses on the top and bottom halves of the discharge casing for the 72 psig pressure were 13.8 ksi and 14.4 ksi, respectively. The stress criteria used for cast iron casings requires that the hydrotest stresses must be less than one half of the UTS, or 15 ksi for the 30 ksi material. This criteria was therefore met. Overall stresses were very low.

In general, the highest stresses occurred on the discharge end on the inside near the transition from the cylindrical to the end section. The calculated separation at the horizontal split resulting from the 72 psig pressure is shown in Figures 2 and 3. The darker shading shows areas of expected separation. These Figures show that small areas of leakage are possible at the casing discharge end.

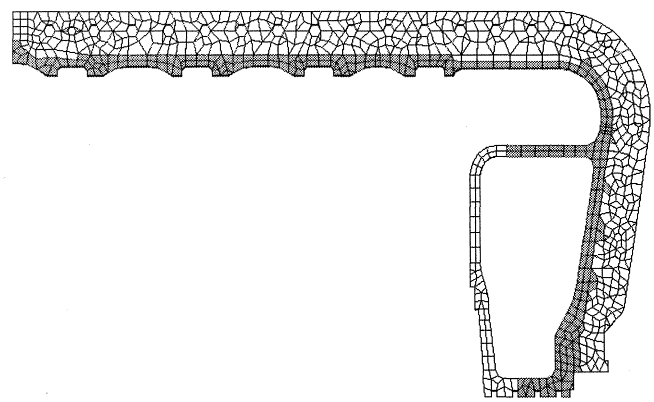

*Figure 2. Separation of Casing at Horizontal Split Line–Right Side as Viewed From Discharge End. Darker shading show areas of separation.*

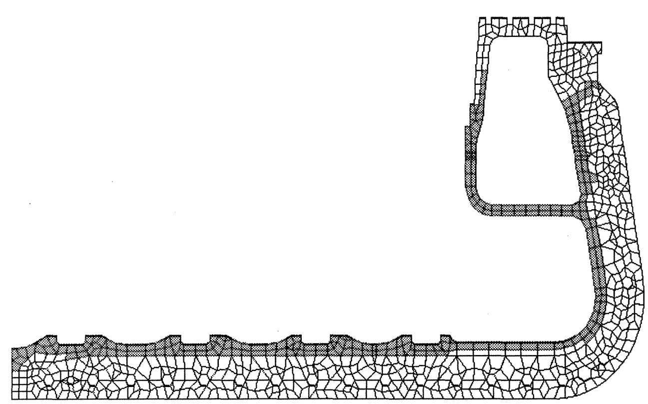

*Figure 3. Separation of Casing at Split Line–Left Side as Viewed From Discharge End. Darker shading show areas of separation.*

The FEA analysis demonstrated that a successful 72 psig hydrotest was feasible. Based on these results, the decision was made to proceed with nondestructive examination (NDE) and hydrotest.

As a further precaution, the decision was made to strain gauge the casing and monitor stresses during the hydrotest. This was done so the test could be stopped if strain gauge stresses significantly exceeded those calculated using the FEA model. The FEA analysis was used to determine areas where strain gauges would be placed. Initially, the location of the ten most highly stressed elements in the FEA model for each discharge casing half was identified by a thorough examination of the model results. The lower casing peak stress positions were given location ID numbers 1 to 10, while the upper casing peak stress positions were given location ID numbers 11 to 20. A further subdivision of stress ID location labels was assigned to identify the stresses at a given position as either inside or outside case stresses. The letter "a" after the ID number was assigned to imply "inside case" stresses while the letter "b" was assigned to imply "outside case" stresses, as related to a given location ID number.

After review of the 20 locations initially identified, the number of locations physically instrumented was reduced to the seven most critical locations. The number of instrumented locations was driven by a) a data acquisition equipment recording limitations, b) a duplication or redundancy of peak stress locations due to casing dimensional symmetry, and c) the relative drop-off in peak stress magnitudes (i.e., the tenth highest stress being significantly lower than the peak stress).

The seven locations at which strain gauges were placed are shown in Figures 4, 5, 6, and 7. Five of the seven locations were on the inside of the discharge case. Strain rosettes were placed at these five locations to provide 2-D Von Mises stresses in the plane of the surfaces that they were bonded to. Locations 1a and 6a, shown in Figure 4, are on opposite sides of the lower case, at the transition from the cylindrical to the end section (i.e., the most highly stressed portions of the lower case), at the horizontal split plane flange. Location 3a, also shown in Figure 4, is inside of the lower discharge case, at the nozzle to casing body transition. This is the most severely stressed corner of the nozzle. Locations 11a and 16a, shown in Figure 5, are in analogous positions to Locations 1a and 6a inside of the upper casing, again at the horizontal split plane flange.

The sixth location, shown in Figure 6, is a stiffening rib location (identified as Location 18), which extends alongside the outside of

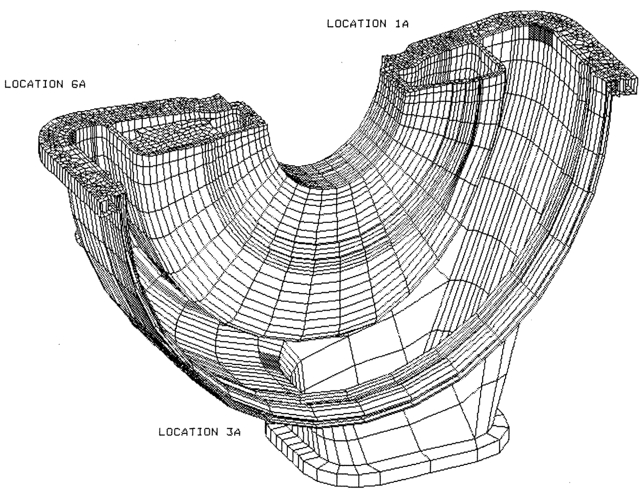


*Figure 4. Strain Gauge Locations 1a, 3a, and 6a on Lower Discharge Case.*

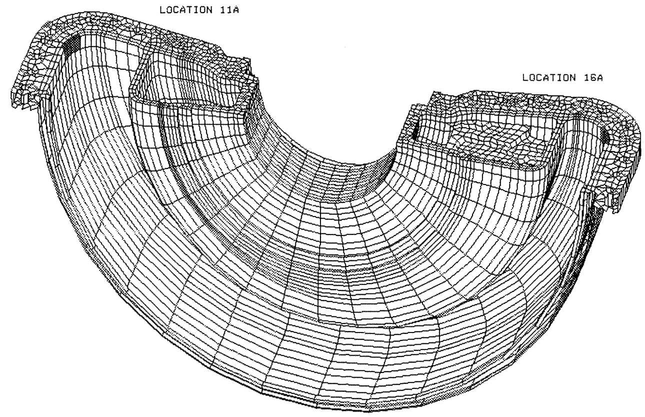


*Figure 5. Strain Gauge Locations 11a and 16a on Upper Discharge Case.*

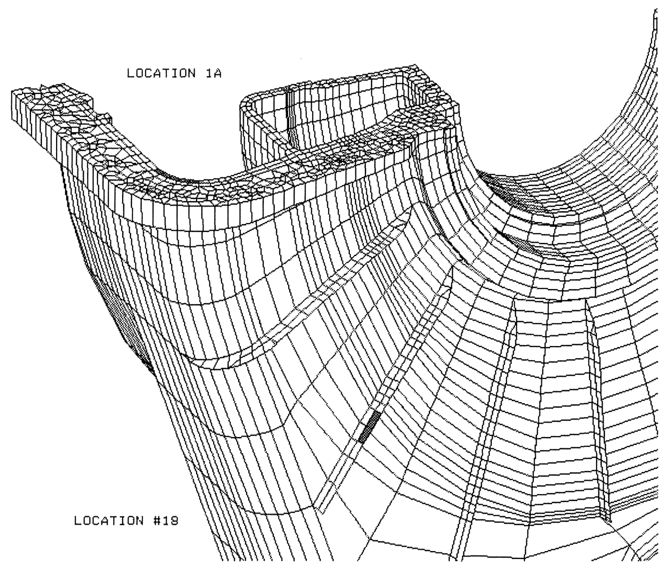


*Figure 6. Strain Gauge Location 18: Stiffening, Rib Lower Discharge Case.*

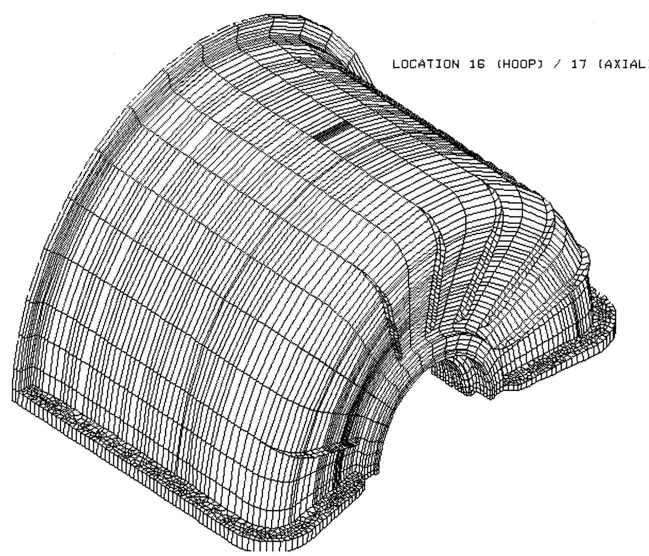


*Figure 7. Strain Gauge Location 16/17: Calibration Point, Upper Discharge Case.*

the nozzle. The finite element analysis identified this rib as the most severely stressed rib due to its dual role in a) stiffening the end of the case from outward expansion and b) acting as a load path for nozzle loads. A uniaxial strain gauge was bonded there oriented to measure "length direction" strains.

A seventh, non-stress critical, calibration point was also selected. Location 16/17 was selected for this purpose and is shown in Figure 7. At this location, two uniaxial strain gauges were placed and oriented to measure handbook predictable hoop/axial direction (cylindrical shell type) case stresses. Location 16/17 is 44.5 in from the vertical split at the top of the casing.

FEA calculated stresses at the strain gauge locations were documented at 50 psig, 60 psig, and 72 psig. This allowed the strain gauges to be monitored as the pressure was being increased, to ensure safety during testing and to prevent damage to the casing.

*Inspect and Review*

During the next scheduled equipment shutdown, the unit was taken out of service, disassembled, shipped to a repair facility, and made ready for examination and hydrotest.

*Safety*

Case recertification requires the generation of a detailed test plan prior to beginning the test. This plan should consider and identify all relevant safety issues including disassembly, cleaning, examination, testing, reassembly, shipping, and reinstallation. The plan should consider valuable information provided by the case user including; normal operating conditions, excessive operating conditions, examination and repair history, along with identification of contaminants that may be present on case surfaces.

During generation of the test plan, consideration was given to identification of the appropriate cleaning method required to prepare surfaces for examination. As discussed, the FEA was used to identify critical high stress areas that were selected for strain gauging to assure safety during hydrostatic testing. The case was subjected to nondestructive examination to verify it's integrity. As a result of the examination, all relevant indications identified required engineering evaluation, disposition, and repair as required, prior to hydrostatic testing.

*Case Inspection*

Verification of case integrity was critical in determining test feasibility, and to ensure safety during hydrostatic testing. NDE was the key element during this phase of the test and required on site support by both a certified nondestructive examination level III and a design engineer. The design engineer and NDE level III were intimately familiar with the case history, FEA data, and recertification requirements. The advantage of having on site support during this evaluation was to provide examination supervision, real time evaluation of relevant indications, and direct communication with the OEM and customer. Nondestructive examination methods included; visual, magnetic particle, and ultrasonic examination to evaluate this case to original manufacturing drawing requirements and to identify any service generated discontinuities. After cleaning all surfaces using an approved cleaning process, including blast cleaning to remove paint scale, and appropriate disposal of all contaminated materials, all case surfaces were subjected to 100 percent NDE examination.

Visual inspection was performed over all surfaces to identify obvious areas such as excessive erosion, cracks, repairs, and modifications of the case from the original manufacturers design.

Magnetic particle inspection was performed on 100 percent of case surfaces to identify discontinuities such as cracks that could not be identified through visual examination. Magnetic particle was performed using half wave alternating current (HWDC), braided copper prods to reduce arcing on machined surfaces, and dry visible particles applied with the continuous application method. The continuous particle application method was used to provide particle mobility using HWDC current. Application of this technique resulted in the most effective and sensitive magnetic particle examination for this application.

Ultrasonic examination was used to verify case wall thickness in critical areas identified by the design engineer based on FEA data and any areas identified during visual examination. Wall thicknesses were measured using a portable cathode ray tube (CRT) ultrasonic instrument, and the resultant thicknesses recorded, mapped, and compared to drawing requirements and wall thicknesses used in the FEA.

As a result of the nondestructive examination, all relevant indications were marked on the case, classified, recorded, mapped, and subjected to engineering evaluation. Each indication was evaluated as to its effect on product service at recertification pressures and a disposition was determined by the design engineer.

The results of nondestructive examination included:

- Case Bottom Section
    - Visual examination identified numerous threaded through wall plugs that had been welded. These were not part of the original manufacturers design. Due to the effects of erosion of the weld material, the plugs were visible.
    - The inlet nozzle splitter vane exhibited a crack 3/4 of the vane length (approximately 25 in long).
    - Magnetic particle inspection identified small shallow cracks in base material adjacent to many of the plugs identified above.
- Case Top Section
    - Visual examination identified numerous threaded through wall plugs similar to those identified in the bottom section. The case ID exhibited weld build up that had eroded in many areas.
    - Base material cavities (porosity/blowholes) were identified and mapped for evaluation.

Indications identified through nondestructive examination resulted in the following actions and dispositions:

- All plugged areas exhibiting cracks were ground and blended, subjected to magnetic particle examination to verify crack removal, and case wall thickness verified through ultrasonic inspection to drawing requirements.
- The splitter vane crack was subjected to metal lock stitching and magnetic particle examination.
- All areas exhibiting excessive erosion were blended, and resultant case wall thickness verified through ultrasonic inspection to drawing and FEA requirements.

After completion of the actions described above the decision was made to proceed with the hydrostatic test.

*Hydrotest*

The instrumented hydrotest was conducted at the repair facility. Fifteen internal and three external static strain gauges, properly sealed for protection from moisture, were used during the test. The casing was filled with water and rust inhibitor, and the 18 gauges were zeroed. Two stepped pressurization runs up to 40 psig were made, followed by a run up to 60 psig. The pressure was stepped back down to zero after each run. The gauges were zeroed after the third run. In the fourth run the casing was step pressurized up to 72 psig, and held there for 1-1/2 hours before returning to zero. The Von Mises stresses calculated from the strain measurements were compared to FEA calculated Von Mises stresses. Note that the test stresses were computed using only principal stresses in two directions (stress normal to the gauges cannot be measured), while FEA Von Mises stresses used principal stresses in all three directions. In addition, minimal leakage was noted, as predicted by the FEA.

Stresses calculated from the strain gauge data were found to be lower than had been predicted by the FEA. Therefore, the customer requested an additional run up to 80 psig in order to allow the case to be certified to 53.3 psig. Based on the above observations, permission to go ahead with this higher hydrotest was given. Prior to the 80 psig run, the stability of the gauges was checked by making another stepped pressurization run up to 72 psig. Good repeatability of results was obtained for 16 of 18 gauges. The stepped pressurization run up to 80 psig was then conducted. Strains were monitored at 72 psig on the way up to 80 psig and on the way back down to zero. Good repeatability was obtained with the previous two tests up to 72 psig. In addition, the return of the strain gauge readings to zero values at zero pressure indicated that no localized yielding had occurred in the higher stress areas.

Ignoring the non-linear effects at the horizontal split, which were assumed to be negligible, strain gauge calculated stresses at 80 psig were expected to be 111 percent of those at 72 psig. Stresses did show approximately this level of increase. The customer hydrotest and strain gauge monitoring were considered a success.

*Post Test Evaluation and Recertification*

After the test, a more in depth comparison of FEA and test stresses was made. Contributors to possible deviations in results were identified. These included:

• An average elastic modulus of $15.2 \times 10^6$ psi was used for the FEA. The test computer program used to calculate stresses from strains during the hydrotest used a slightly different average elastic modulus of $13.9 \times 10^6$ psi.

• The static head of water resulted in a 4.0 psig pressure differential from the top to the bottom of the casing during the hydrotest.

• Normal strains cannot be measured during the test, allowing only 2D calculation of stresses. The FEA calculations included the full 3D effect.

• Initial stresses and strains caused by the water in the case were not considered in the FEA.

• Actual casing dimensions may be somewhat different than the nominal drawing dimensions used to develop the FEA model.

After the FEA results were scaled down to account for the differences in the elastic modulus, the test stresses were typically found to be about 60 percent of those calculated using FEA, with some test results as close as 95 percent.

This comparison is shown in Table 1. Gauge 17 had failed, explaining the poor correlation of results at this gauge.

*Table 1. Comparison of FEA Calculated and Strain Gauge Calculated Stresses. (FEA results scaled down 8.6 percent for consistent modulus comparison.)*

| Location | 80 psig Hydrotest results | 80 psig FEA results (scaled upward from 72 psig results) | Hydrotest results / FEA results |
|---|---|---|---|
| 1a | 10,291 | 12,680 | 0.81 |
| 3a | N/R | 11,391 | - |
| 6a | 7,000 | 8,140 | 0.86 |
| 11a | 5,630 | 12,147 | 0.46 |
| 16a | 4,928 | 8,390 | 0.59 |
| #16 | 1,043 | 1,801 | 0.58 |
| #17 | 278 | 712 | 0.39 |
| #18 | 2,697 | 13,654 | 0.20 |

The large difference in results for gauge 18, which was on a casing rib, were suspected to be caused by the weight of the liquid which had not been included in the analysis. Considering the possible contributors to stress differences mentioned previously, and the general difficulties in comparing analysis to test results, the above correlation was considered to be good.

Results of the FEA, case inspection, and instrumented hydrotest were then reviewed. The FEA indicated theoretically that the casing, if built per print and if in as new condition, should be capable of successfully undergoing the necessary hydrotest. Inspection of the casing indicated that the casing was indeed built to print, and furthermore was in condition sufficient to allow hydrotest to the required levels. The instrumented hydrotest revealed generally good correlation between predicted and measured stresses.

Based on all of the above, it was recommended that the discharge casing be rerated to a maximum discharge pressure of 53.3 psig. The unit was then re-nameplated and all records were modified to reflect the new pressure rating.